Open questions towards the definition of the physics potential and experimental requirements of a future hadron collider

Next steps in the Energy Frontier - Hadron Colliders

Fermilab, August 25-28 2014

Michelangelo L. Mangano
CERN, PH-TH

Key question after LHC8
(and, hopefully not, but possibly after LHC14)

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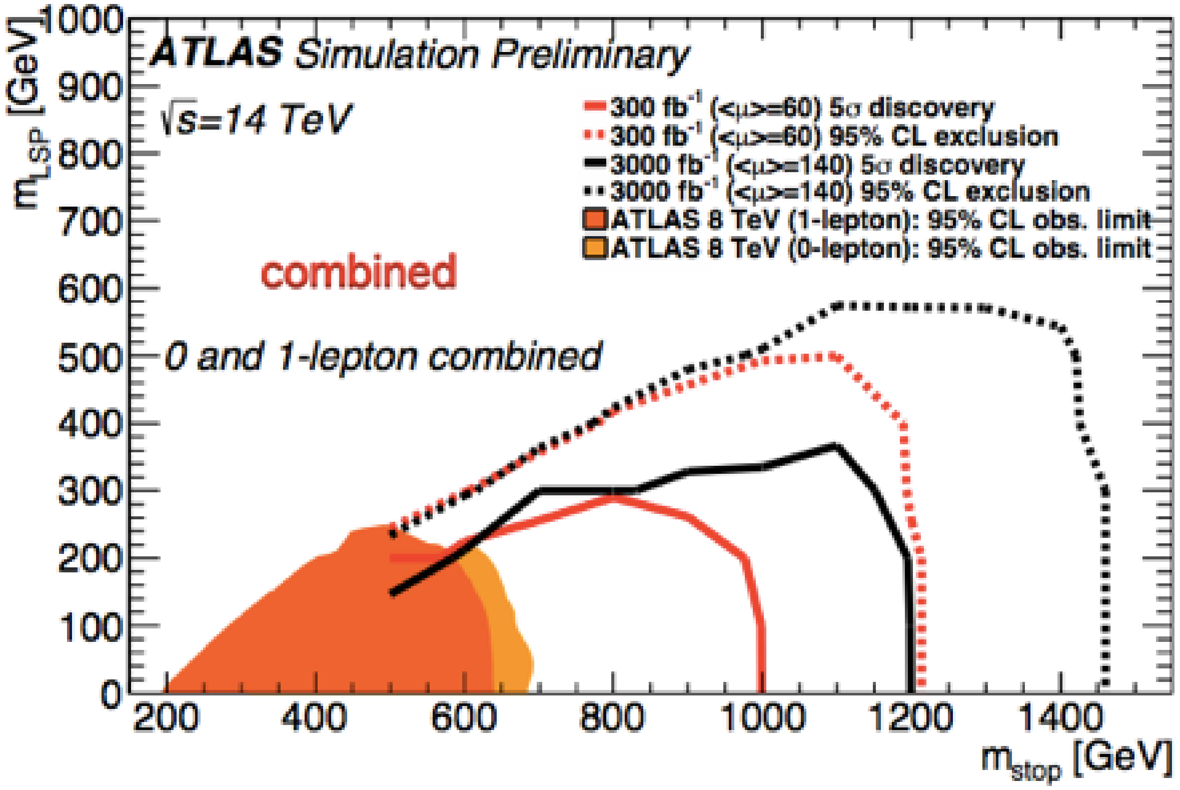
E.g:
do we best accommodate the requirements of these two alternatives in a single hyper-multi-purpose detector, or should we pursue different detector designs, optimized to address sub-TeV and multi-TeV physics, respectively ?

.... see e.g. ATLAS/CMS vs LHCb

Example: LHC vs HL-LHC

Direct stop searches (Altan Cakir, this wshop)



Z' → e^+e^-

ATLAS/CMS HL docs	300/fb	3000/fb
95% excl (ATLAS)	**6.5 TeV**	7.8 TeV
5σ (CMS)	5.1 TeV	**6.2 TeV**

Message:

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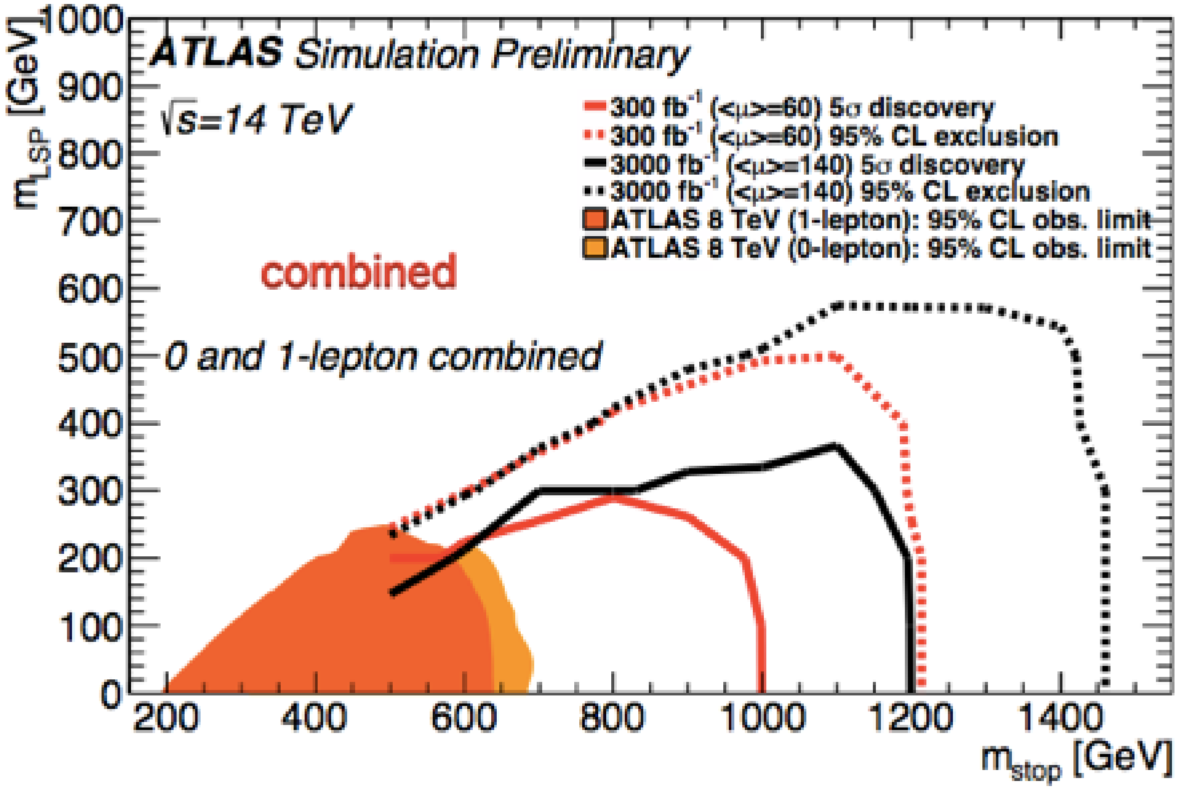

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Message:

- What's been excluded at Lum will not be discovered at 10 x Lum, unless ...
  - At high mass there is ~nothing to do (eff and accept are ~ 1)
  - At low mass (eff, accept << 1, elusive signals) one could invest in improved detector/trigger performance, to boost useful rates and sensitivity by factors larger than L increase

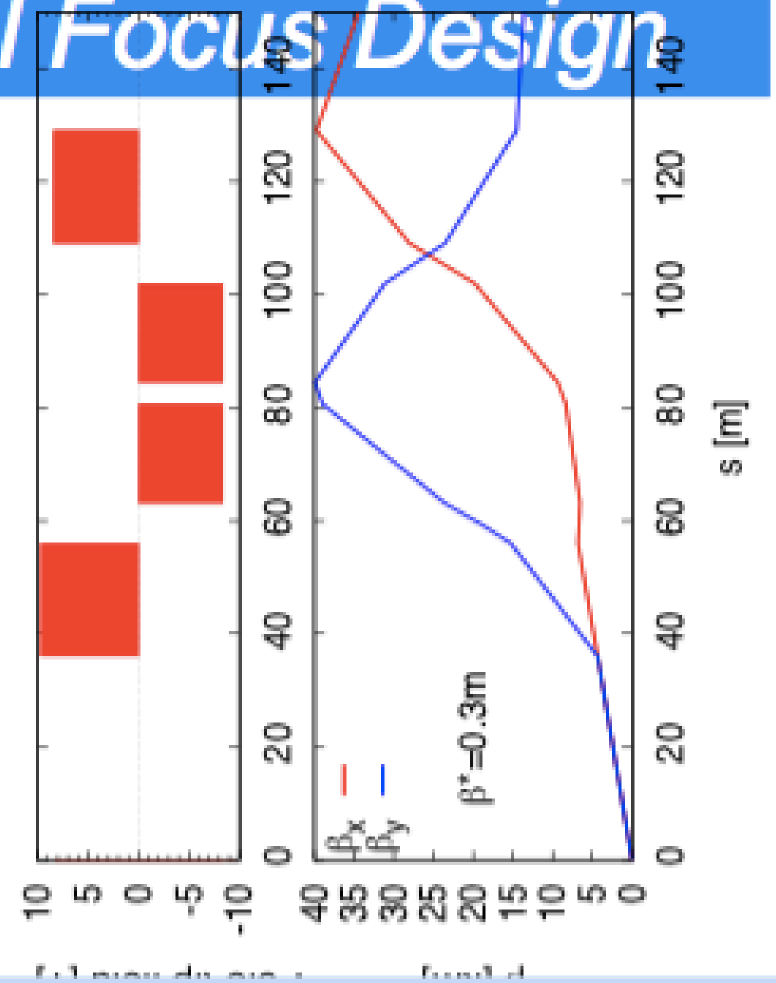
Some important choices in the design of the accelerator require “urgent” input from physics considerations

Interaction Region and Final Focus Design

R. Tomas

Two design being investigated:

- L^* = 46m / 38m (how much is needed?)
- β^* = 0.8m / 0.3m (goal <1.1m)



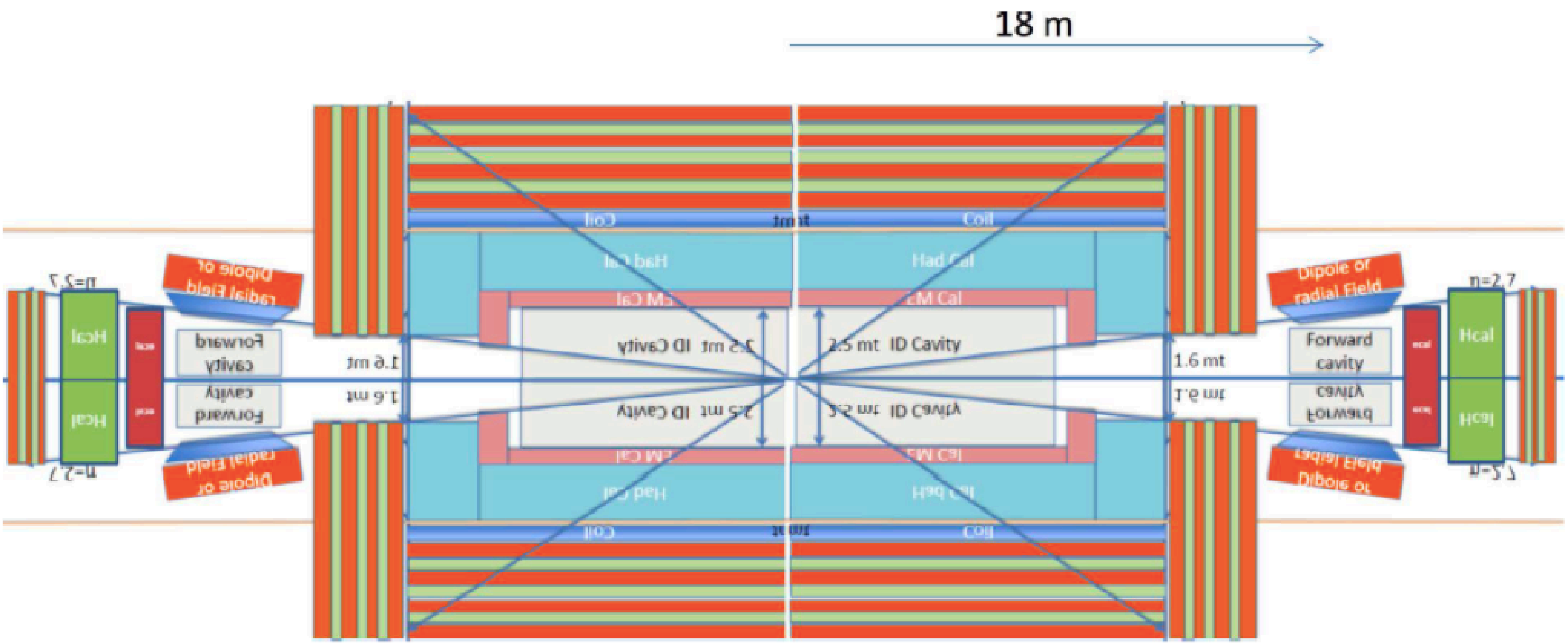
It is easier to obtain small beta-functions with shorter L*

Will have a tendency to reduce L*

Need to understand detector requirements as soon as possible

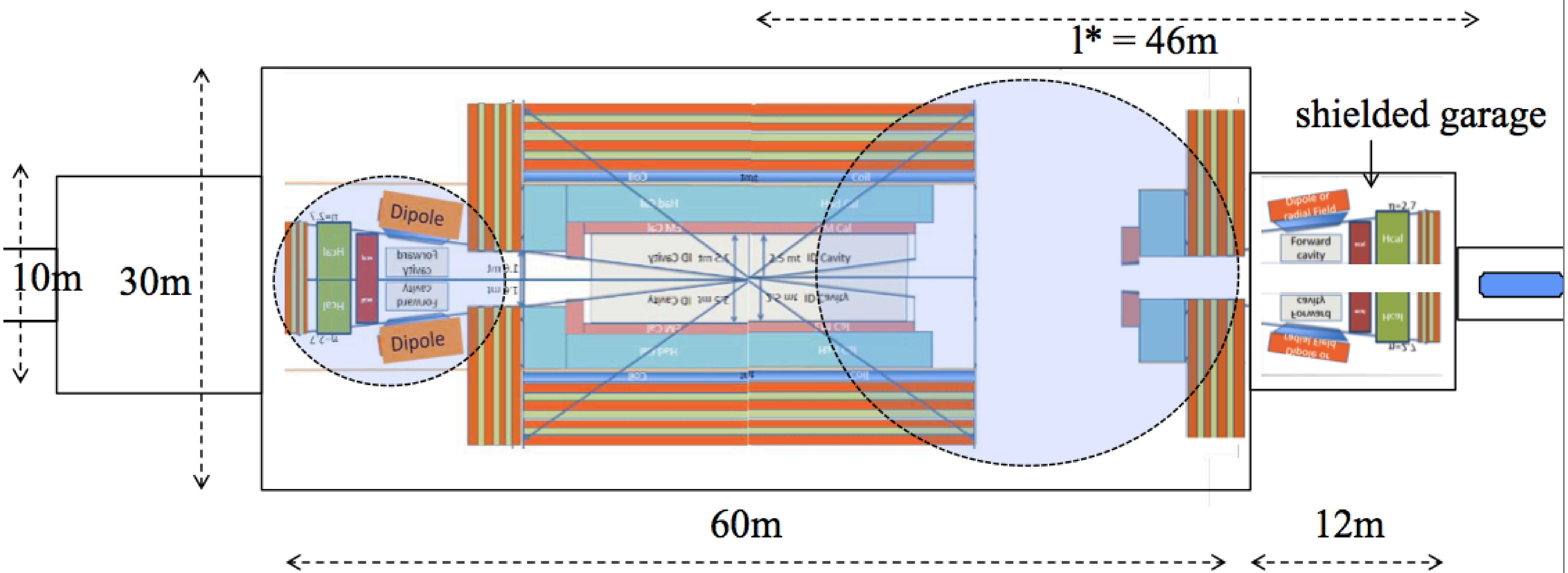
Many issues need to be addressed
- Magnet performance
- Radiation effects
- Space constraints from experiments
- Beam-beam effects and mitigation
- …

L* = 46-38m seems consistent with scale of proposed detector layouts, e.g.



however ....

Maintenance scenarios look difficult



B.Palmer, this wshop:

2) LUMINOSITY

$$\mathcal{L} \propto \frac{\gamma\, I}{\beta *}\,\Delta\nu \qquad I \propto (f\; N_p) \qquad \Delta\nu \propto \left(\frac{N_p}{\epsilon_\perp}\right)$$

where f = bunch frequency, N_p = protons per bunch, $\epsilon_\perp$ = normalized rms transverse emittance, $\beta*$ = IP Courant-Snyder function, $\Delta\ \nu$ = beam-beam tune shift, and I = beam current

Fundamental cross sections fall with $1/\gamma^2$, so lumiosity should rise as γ^2. Going from LHC at 14 TeV to 100 TeV we need:

$$\boxed{\mathcal{L}_{100} \geq 1\ 10^{34} \times \left(\frac{100}{14}\right)^2 = 5\ 10^{35} \quad (\mathrm{cm}^{-2}\mathrm{s}^{-1})}$$

With fixed I and $\Delta\nu$ this requires

$$\boxed{\beta^*_{LHC} = 55(\mathrm{cm}) \quad \rightarrow \quad \beta^*_{this} \approx 5.5(\mathrm{cm})}$$

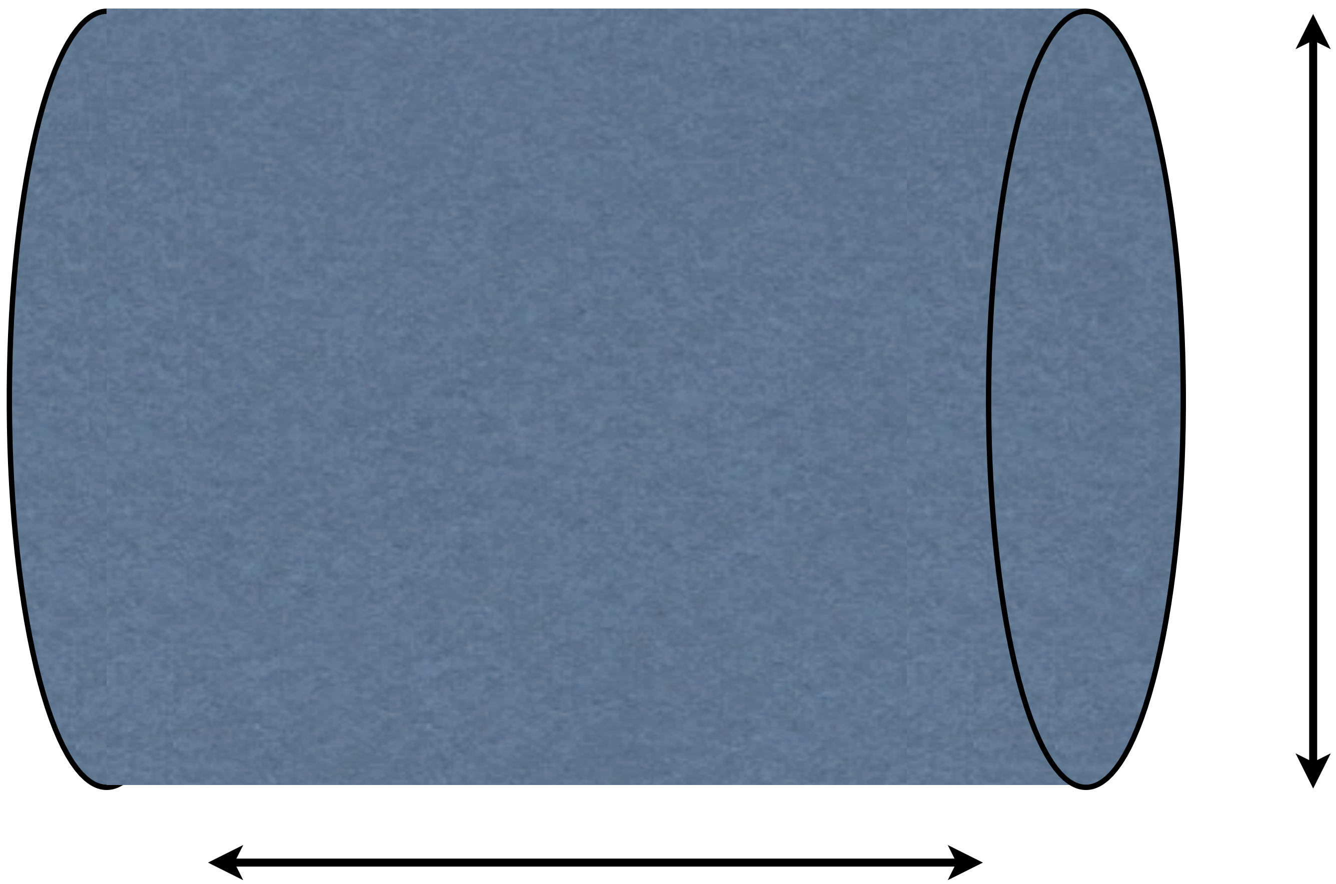
(c.f. β^*=5 (mm) in 3 a TeV muon collider lattice[8].)

cfr: L = 46 (38) m needed for β* = 80 (30) cm*

Forward acceptance clashes against machine needs for high luminosity

Since rate ∝ (acceptance × luminosity), there is room for optimization ...

Key physics drivers of the detector envelope



- muon pt resolution (BL^2)
- jet containment (cal depth, L)
- broadening of collimated jets (BL^2)
  - jet substructure
  - b-tagging

- eta acceptance:
  - lepton, gamma acceptance (Higgs, W/Z, ...)
  - jets (VBF)
  - missing E_T

It is urgent to provide clear and justified recommendations to those designing the accelerator and the detectors

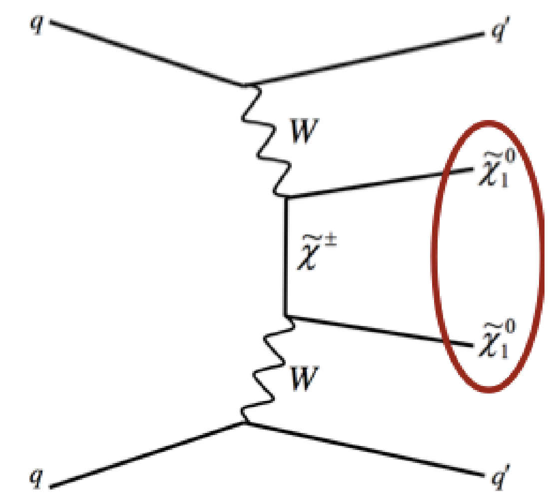
It is important to be ambitious and visionary in the conception of detectors and accelerator, but ...

.... asking to build a perpetuum motion machine is not being ambitious and visionary, it's being dumb !

Drivers for forward-jet acceptance

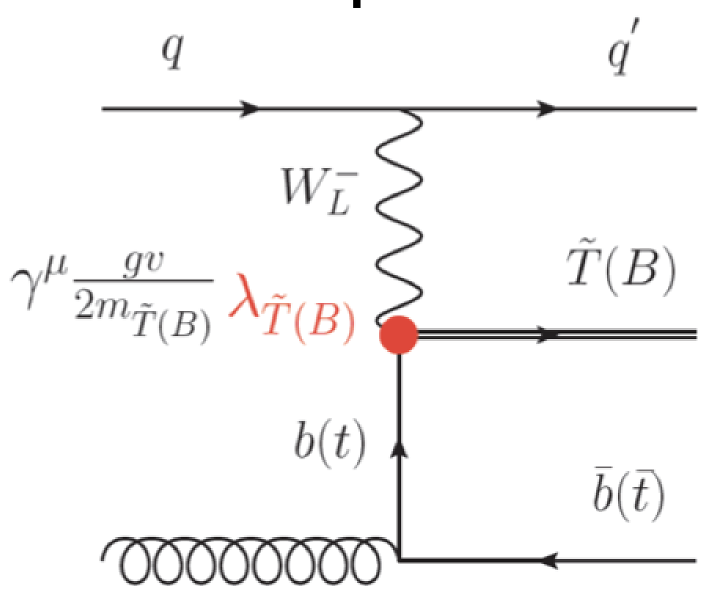
<u>Vector boson fusion and scattering:</u>

- WW → H
- WW → WW
- WW → HH
- WW → ew-inos/DM candidates/etc



Aram Avetisyan, Giuliano Panico

<u>s-channel resonances in Wq fusion:</u>



<u>Missing-ET resolution</u>

Heather Gray, FCC-hh mtg Febr 6 http://indico.cern.ch/event/297201/

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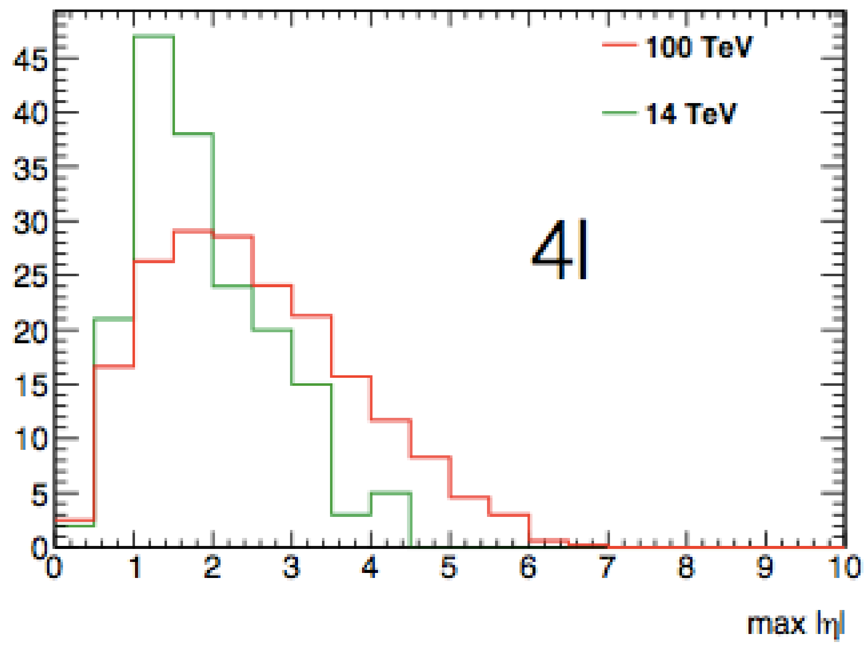
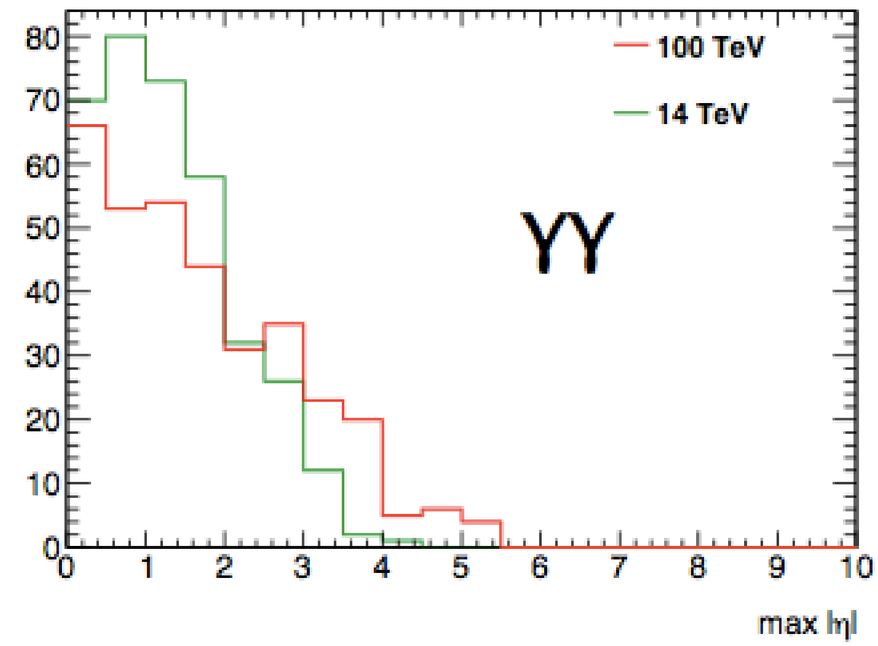
ggF Production at 14 and 100 TeV





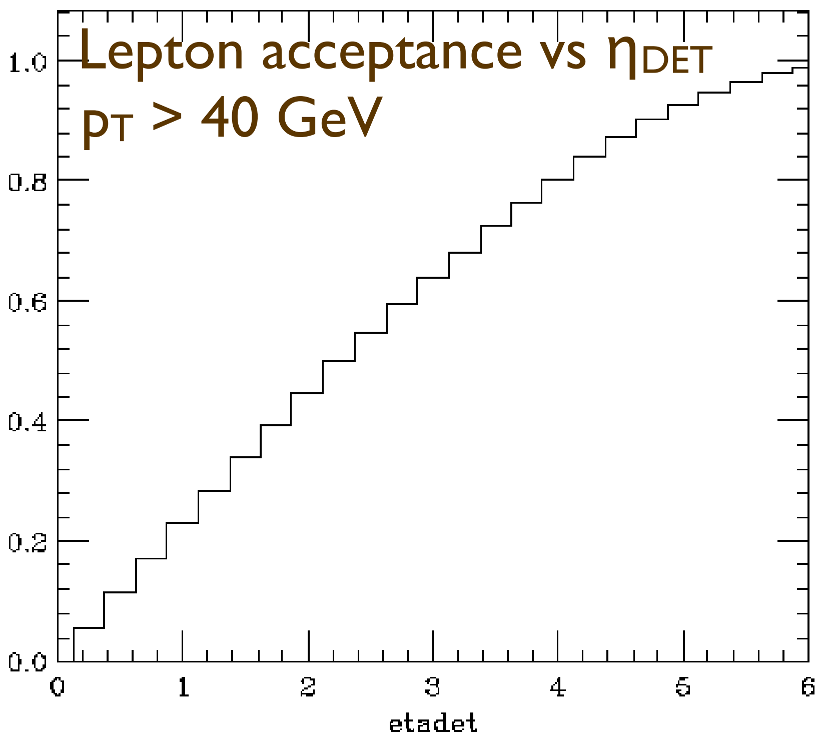
		$\|\eta\| < 2.5$	$\|\eta\| < 4$	$\|\eta\| < 5$
ll	100 TeV	0.66	0.92	0.98
	14 TeV	0.87	1	1
YY	100 TeV	0.83	0.97	1
	14 TeV	0.96	1	1

Significant acceptance loss with $|\eta| < 2.5$

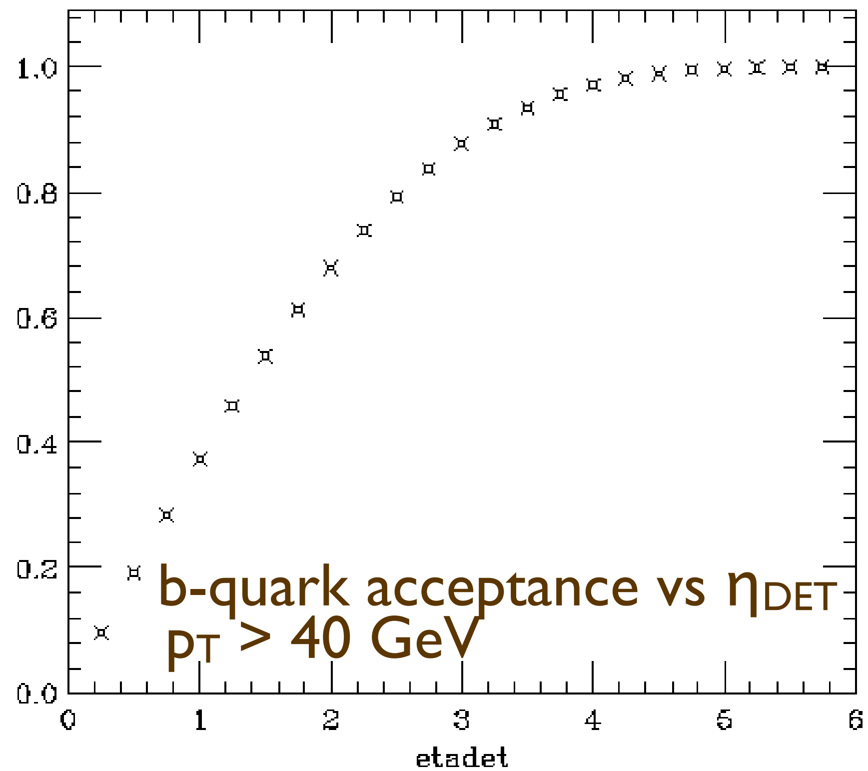
Can the cost of covering $\eta>2.5$ be used to regain the acceptance loss in cheaper ways, e.g. lowering p_T trigger thresholds ?

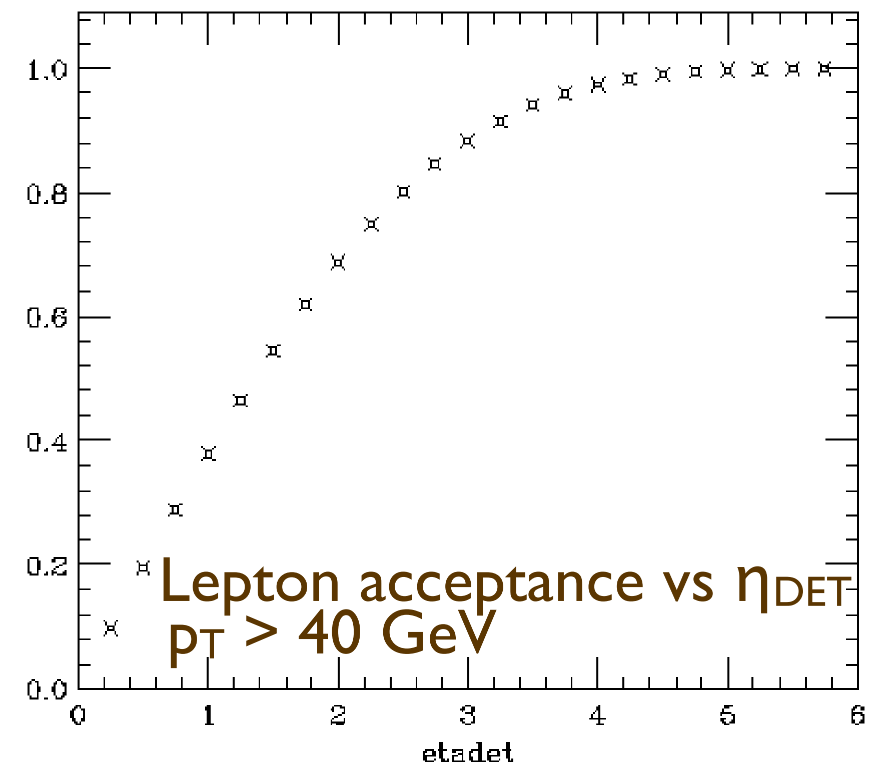
Forward lepton acceptance

Inclusive Z production

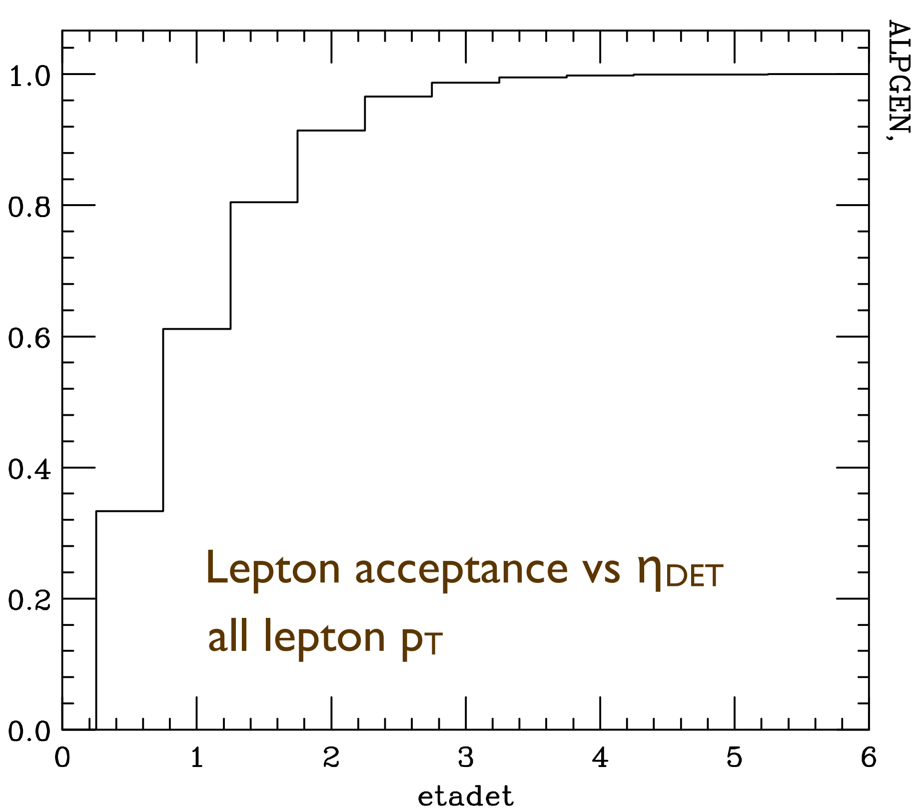


Inclusive t-tbar production





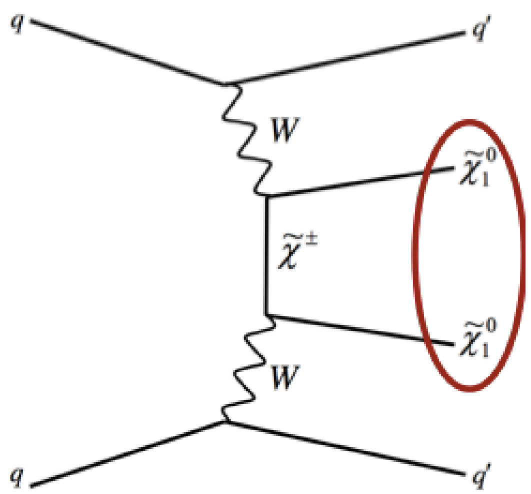
Inclusive Z' (M=20 TeV) production



Forward acceptance beyond η>3 is most critical when dealing with production of "light" systems. Cross sections here are huge, statistics is not an issue ...

Are there scenarios where the study of very massive central systems requires good detection capabilities in the forward ?

pp→X X jet jet, with X=slepton, stop, sbottom, gauginos



Comp. Spectra Via VBF at 100 TeV

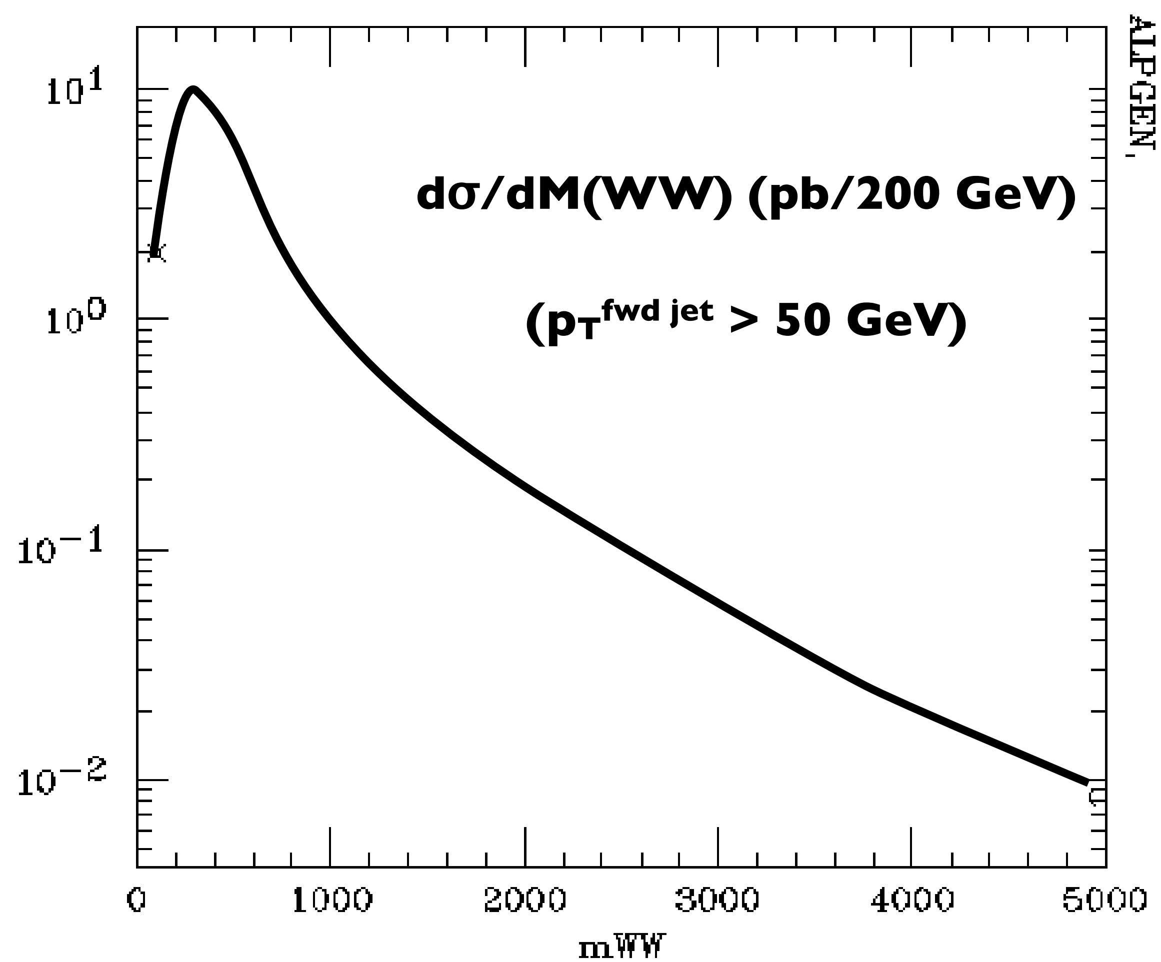
We consider 5 spectra with small mass gaps:

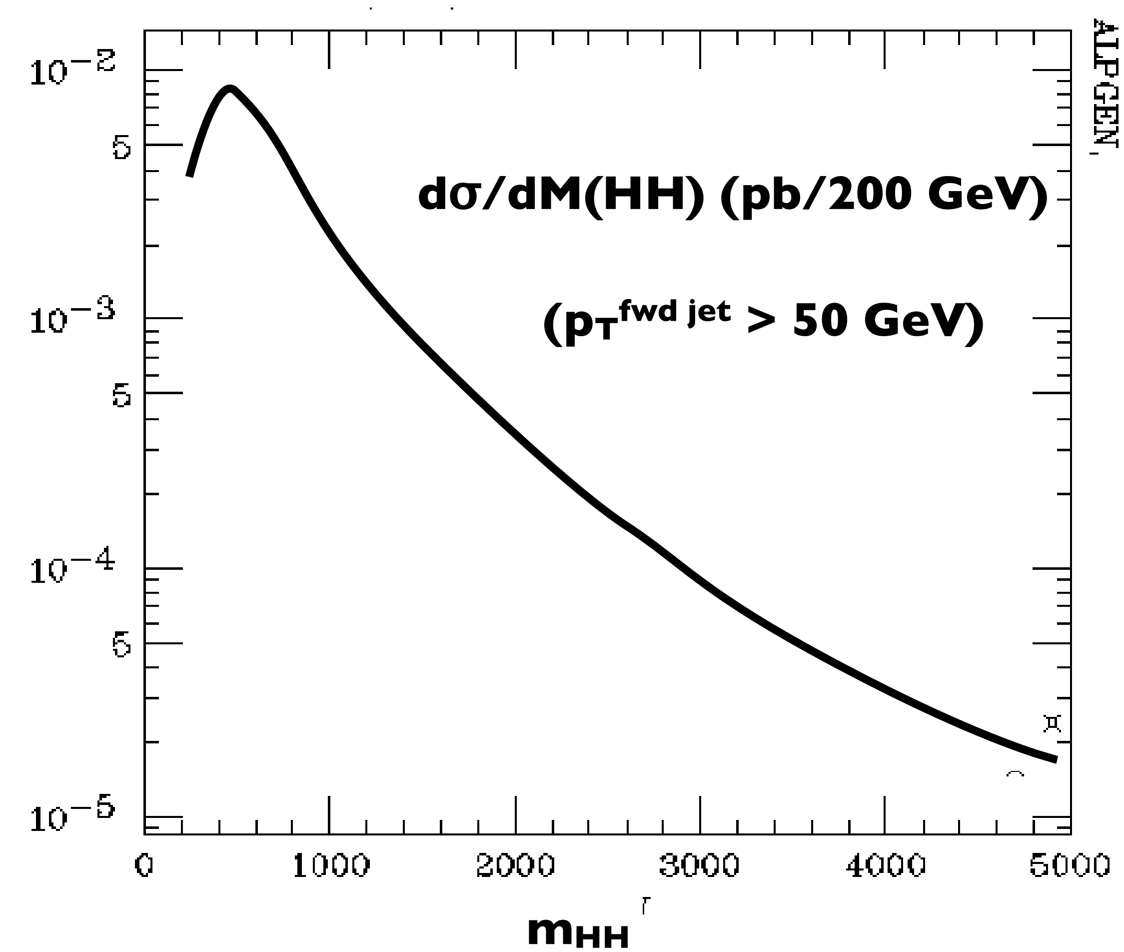
1. $\tilde{e}_1, \tilde{\mu}_1$: 329, $\tilde{\nu}$: 319, $\tilde{\chi}_i^0$: 206,290,332,671, $\tilde{\chi}_i^\pm$: 208,337
2. $\tilde{e}_1, \tilde{\mu}_1$: 231, $\tilde{\nu}$: 218, $\tilde{\chi}_i^0$: 185,237,299,356, $\tilde{\chi}_i^\pm$: 229,354
3. $\tilde{\mu}_1, \tilde{e}_1$: 489, $\tilde{\nu}$: 483, $\tilde{\chi}_i^0$: 88,500,818,829, $\tilde{\chi}_i^\pm$: 500,829
4. $\tilde{\mu}_1, \tilde{e}_1$: 205, $\tilde{\nu}$: 190, $\tilde{\chi}_i^0$: 188,216,1019,1021, $\tilde{\chi}_i^\pm$: 216,1022
5. $\tilde{\mu}_1, \tilde{e}_1$: 496, $\tilde{\nu}$: 491, $\tilde{\chi}_i^0$: 481,501,1019,1027, $\tilde{\chi}_i^\pm$: 501,1026

⇒ very light central systems !

EWSB probes: high mass WW/HH in VBF

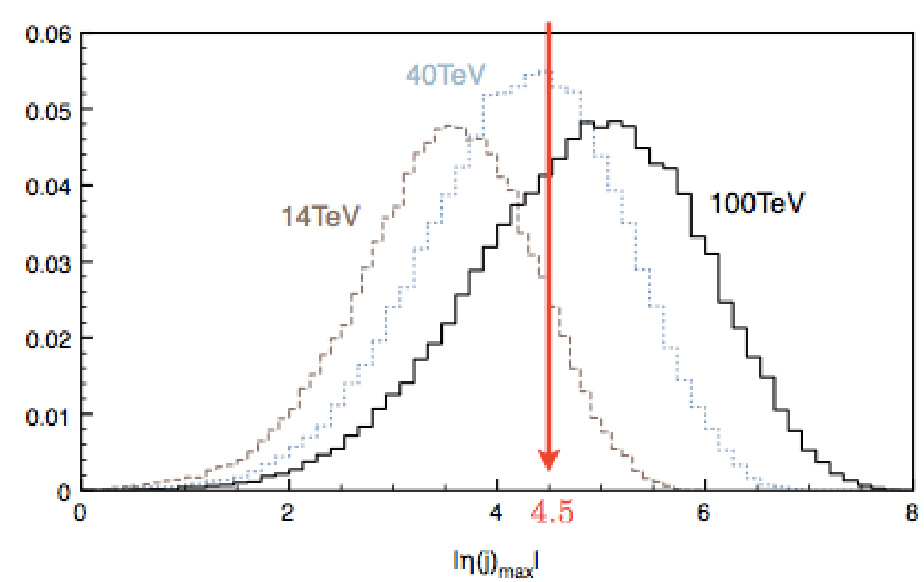
SM rates at 100 TeV





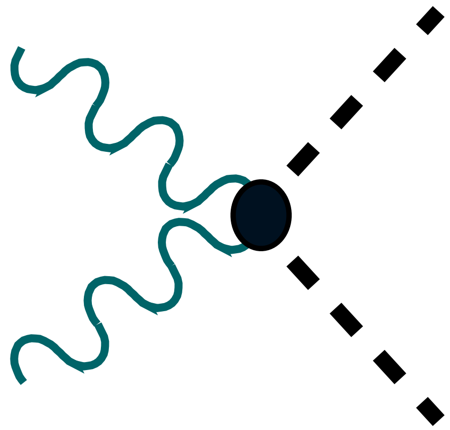
100 fb with M(WW) > ~3 TeV

1 fb with M(HH) > ~2 TeV

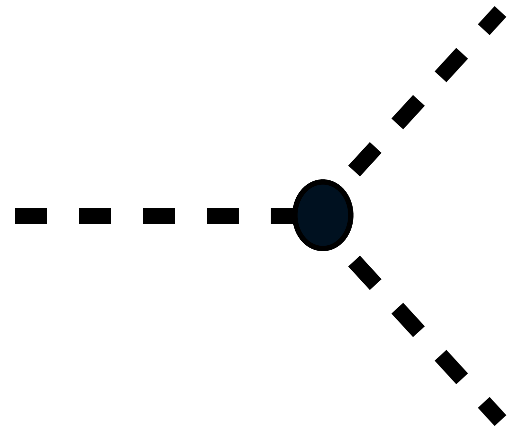


WW→HH scattering

Contino, O. Bondu, A. Massironi and J. Rojo

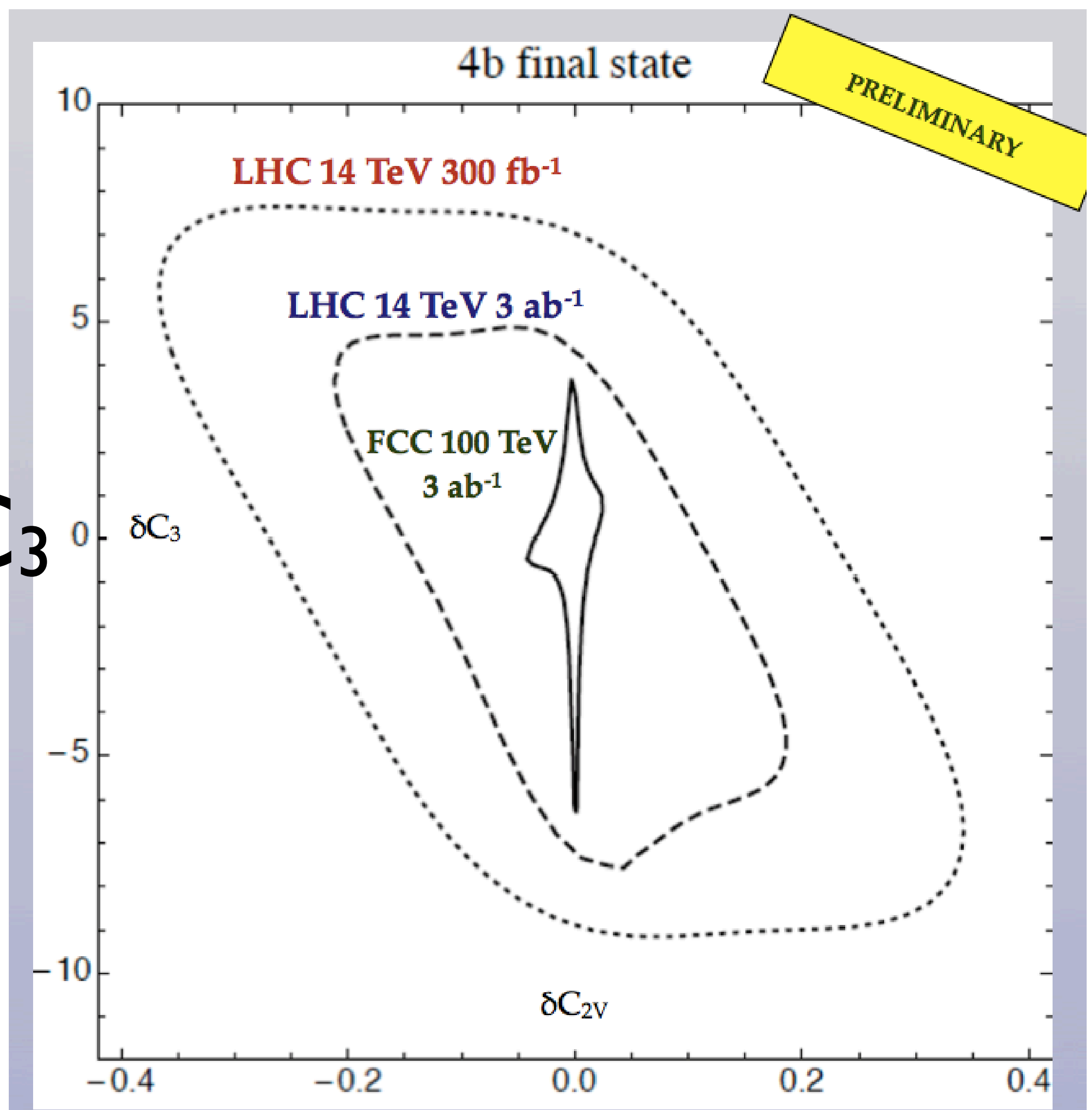


$\sim C_{2V}$



$\sim C_3$

δC_3



δC_{2V}

⇒ HHWW coupling constrained to ~5%

How does this compare with the direct discovery reach of new states that may give rise to deviations of this size ?

What is the best central detector to optimize efficiency for the detection of the HH final state?

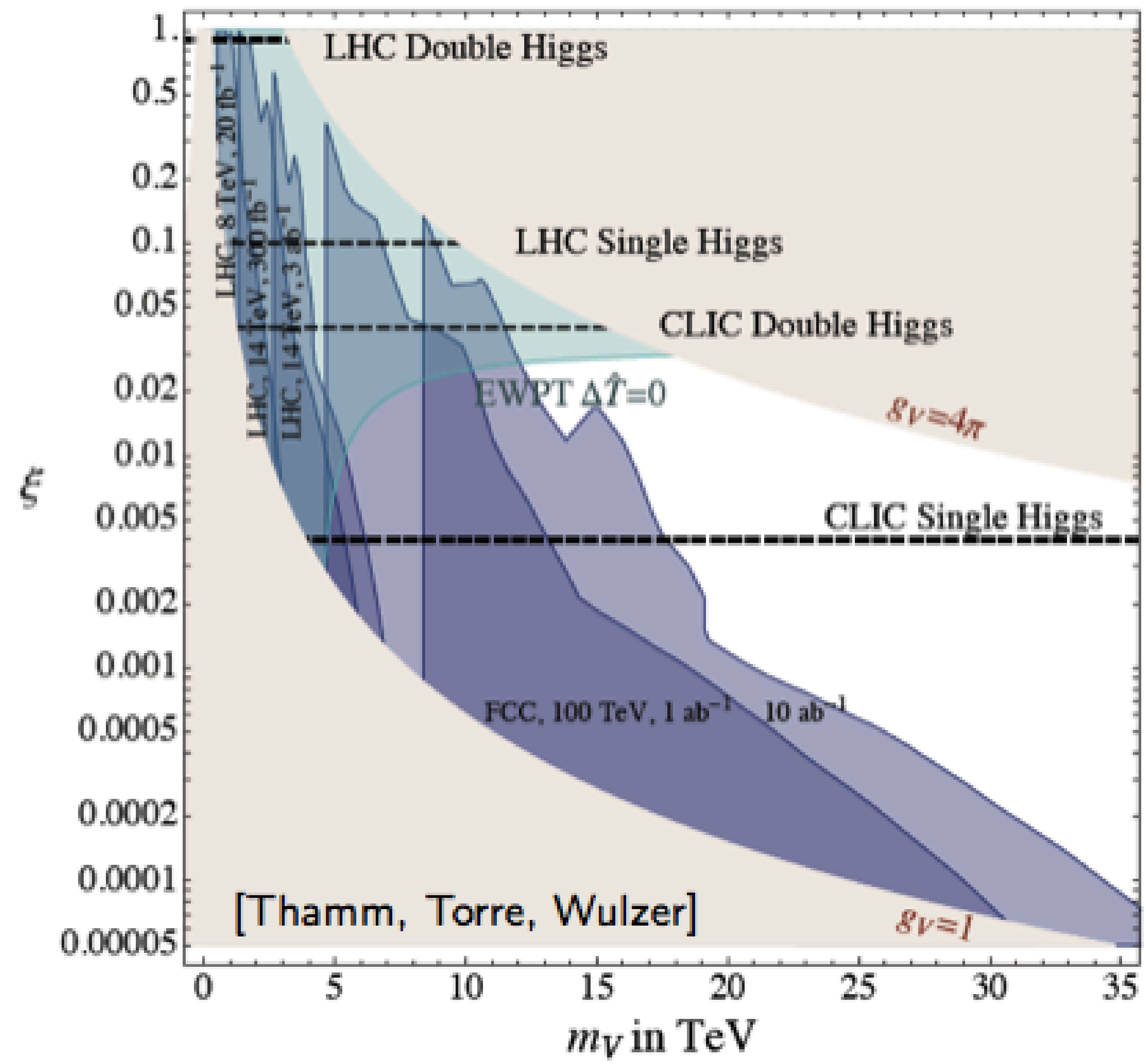
G.Panico

Exploration of deviations in Higgs couplings due to strongly interacting dynamics

- most of the parameter space accessible at the LHC is already **disfavored** by the EW data

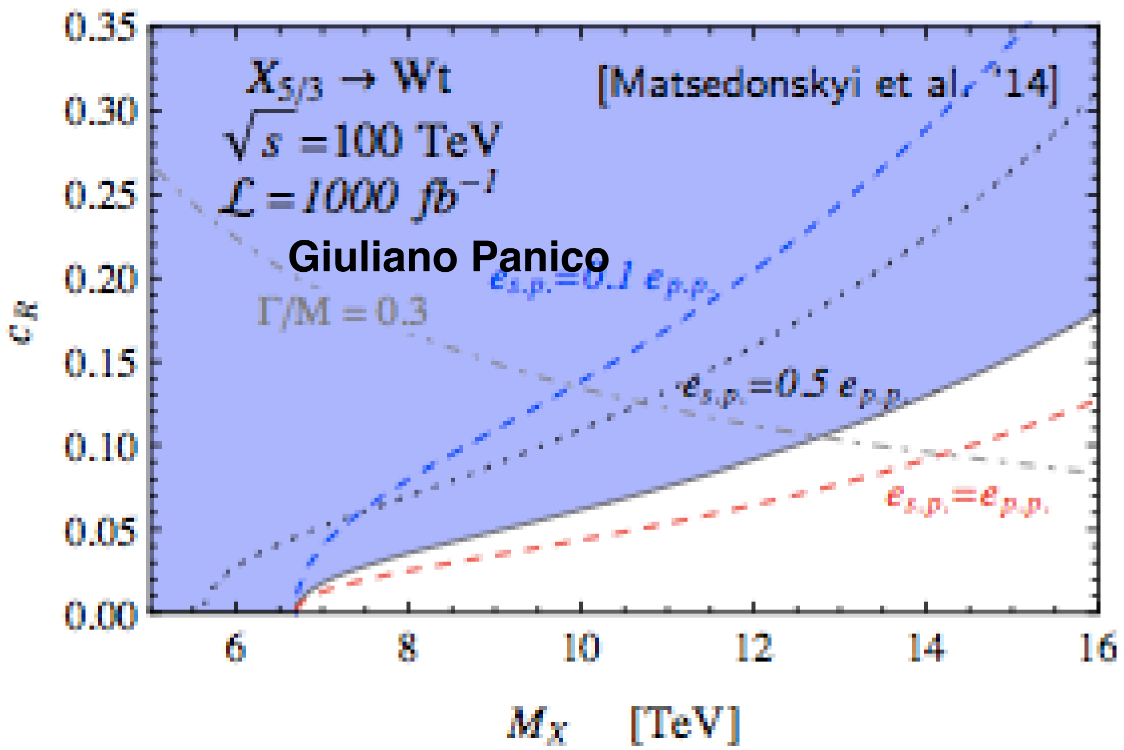
⇒ **direct search for EW resonances**

- an 100 TeV collider can easily probe regions with **tiny Higgs compositeness** ($\xi \lesssim 0.002$)



Top partners at 100 TeV

At 100 TeV the production cross section allows to explore a huge range of masses



- ➢ model-independent reach $M_X \sim 7$ TeV
- ➢ by using single production $M_X \sim 12$ TeV
- ➢ testing **naturalness** up to $\mathcal{O}(0.1\%)$

- There is a lot of work to be done still to properly define the scope, potential and requirements of physics with forward jets.
- What's the impact of MET requirements (both for high mass and low mass scenarios)
- Impact of VBF studies on Higgs couplings (including H selfcouplings) must be compared with direct search for resonances
- Is VBF physics best done in a "multi-TeV" detector, or in a more compact dedicated "TeV-scale detector ?

Muons

$\Rightarrow$ F. Taylor talk

Design Criteria

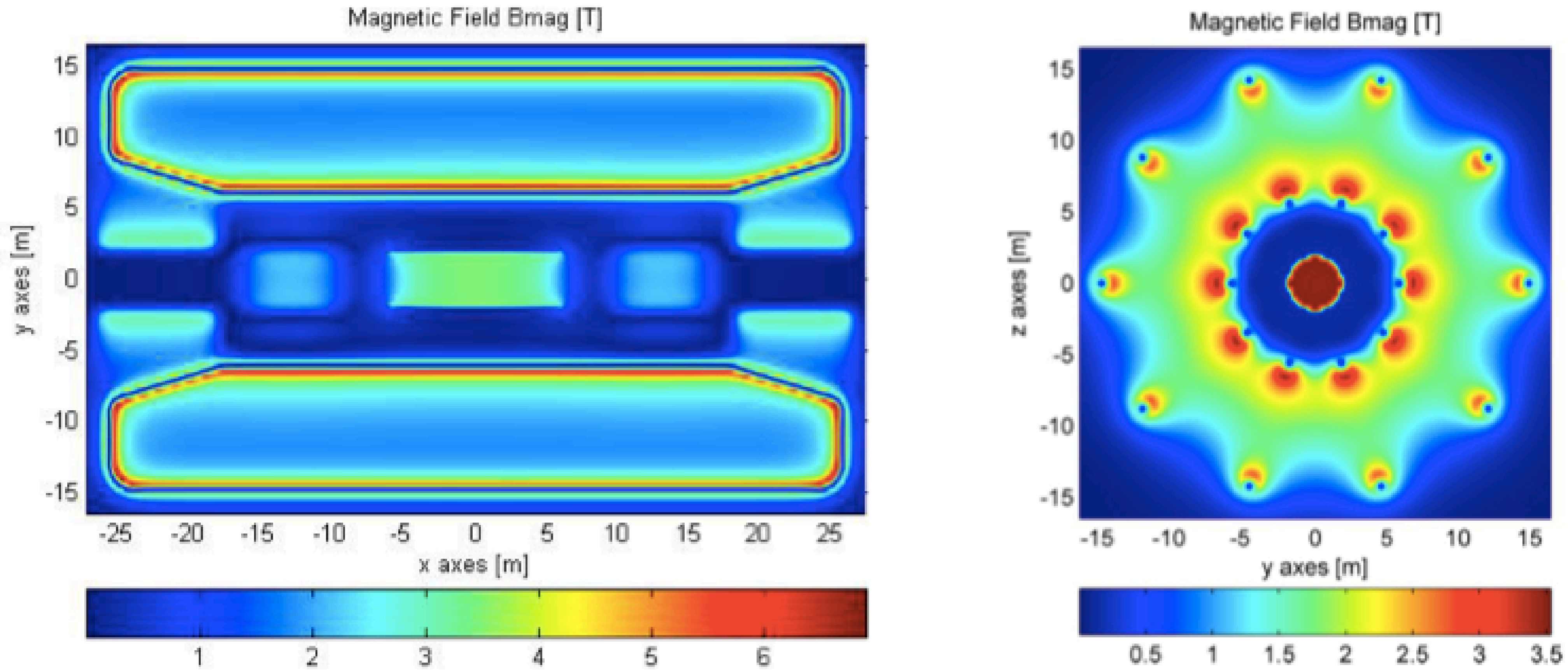
- LHC @ $\sqrt{s}$ = 14 TeV or SSC @ $\sqrt{s}$ = 40 TeV
  - $|\eta|$ range < 2.7
  - Momentum Resolution $\sigma(pT)/pT \sim 10\%$ @ pT = 1 TeV
  - Beam Cross Tagging $\tau \ll 25$ ns
  - Trigger 1 MU pT > 20 GeV/c, 2 MU pT > 10 GeV/c, 3 MU pT > 6 GeV/c
  - Highest detector hit rate ~ 15 kHz/cm^2

- Scaling factors for same chamber resolution
  - $\sqrt{s}$ ratio ~ 7 for LHC or 2.5 for SSC required increase in BL^2
  - $|y_{max}|$ ratio ~ $\ln[(\sqrt{s}=100)/M_p]/[(\sqrt{s}=14)/M_p] \sim 11.5/9.5 \sim 1.2$

- FCC @ $\sqrt{s}$ = 100 TeV
  - $|\eta|$ range < 2.7 x $y_{max}(100)/y_{max}(14) \sim 3.2 \Rightarrow \theta > 4.7^o$
  - Momentum resolution $\sigma(pT)/pT \sim 10\%$ @ pT = 7 TeV/c
  - Beam Cross Tagging $\tau \ll 25$ ns
  - Trigger 1 MU pT > 20 GeV/c, 2 MU pT > 10 GeV/c, 3 MU etc.
    - With BL^2 ~ 7X or 2.5X could raise threshold to higher value but threshold will be determined by bkg. suppression, trigger bandwidth & physics
  - Highest detector hit rate ~ 30 kHz/cm^2

$$B\,L^2\ (FCC) = 100/14\ B\,L^2\ (LHC) = 7\ B\,L^2\ (LHC)$$

2. Option 3: Toroids + Solenoid + Dipoles



- 3.5 T in central solenoid, 2 T - 10 Tm in dipoles and ≈1.7 T in toroid.
- 55 GJ stored energy (for 16 Tm; 130 Tm^2)!
- 0.6 GJ in Solenoid , 0.9 GJ in 2 Dipoles, 2x2.1 GJ in the two End Cap Toroids, and 47.5 GJ in the Barrel Toroid.

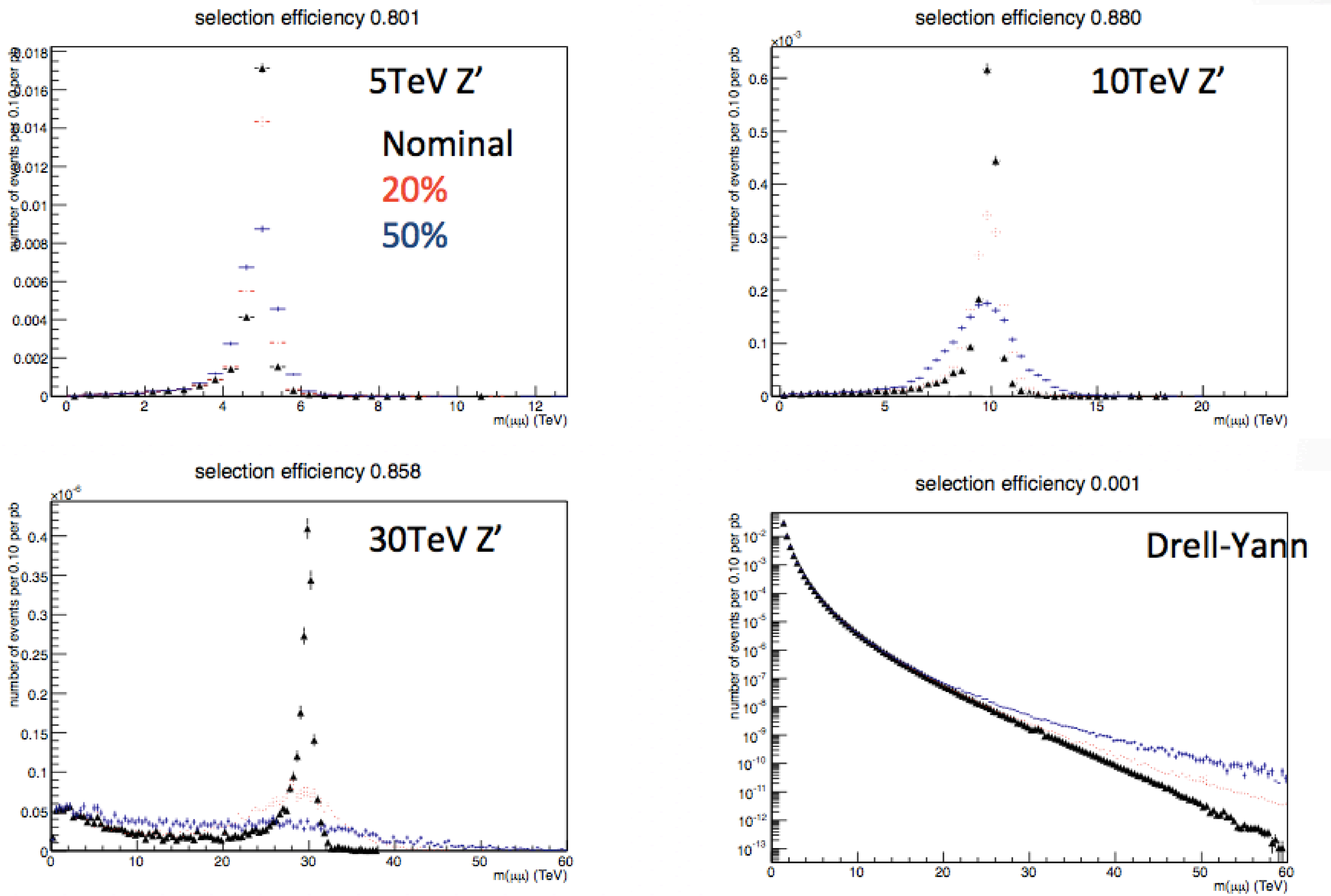
Herman ten Kate

Alexey Dudarev, Leonardo Gerritse, Jeroen van Nugteren,

FCC Workshop @ CERN, 27 May 2014

Clement Helsens, FCC mtgs and updates

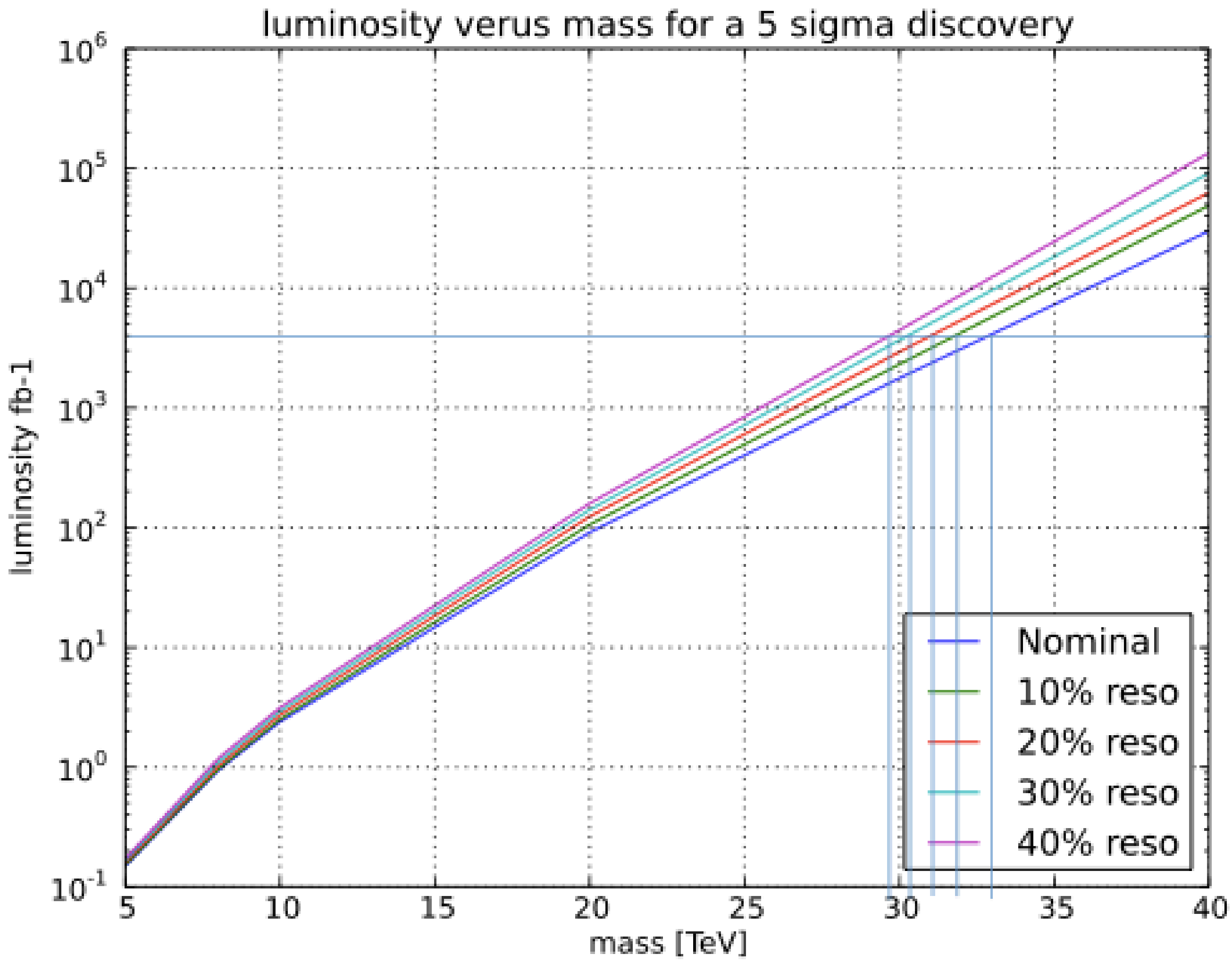
impact of different assumptions on muon momentum resolution at 10 TeV
(nominal: natural Z' width, 3% in this case)



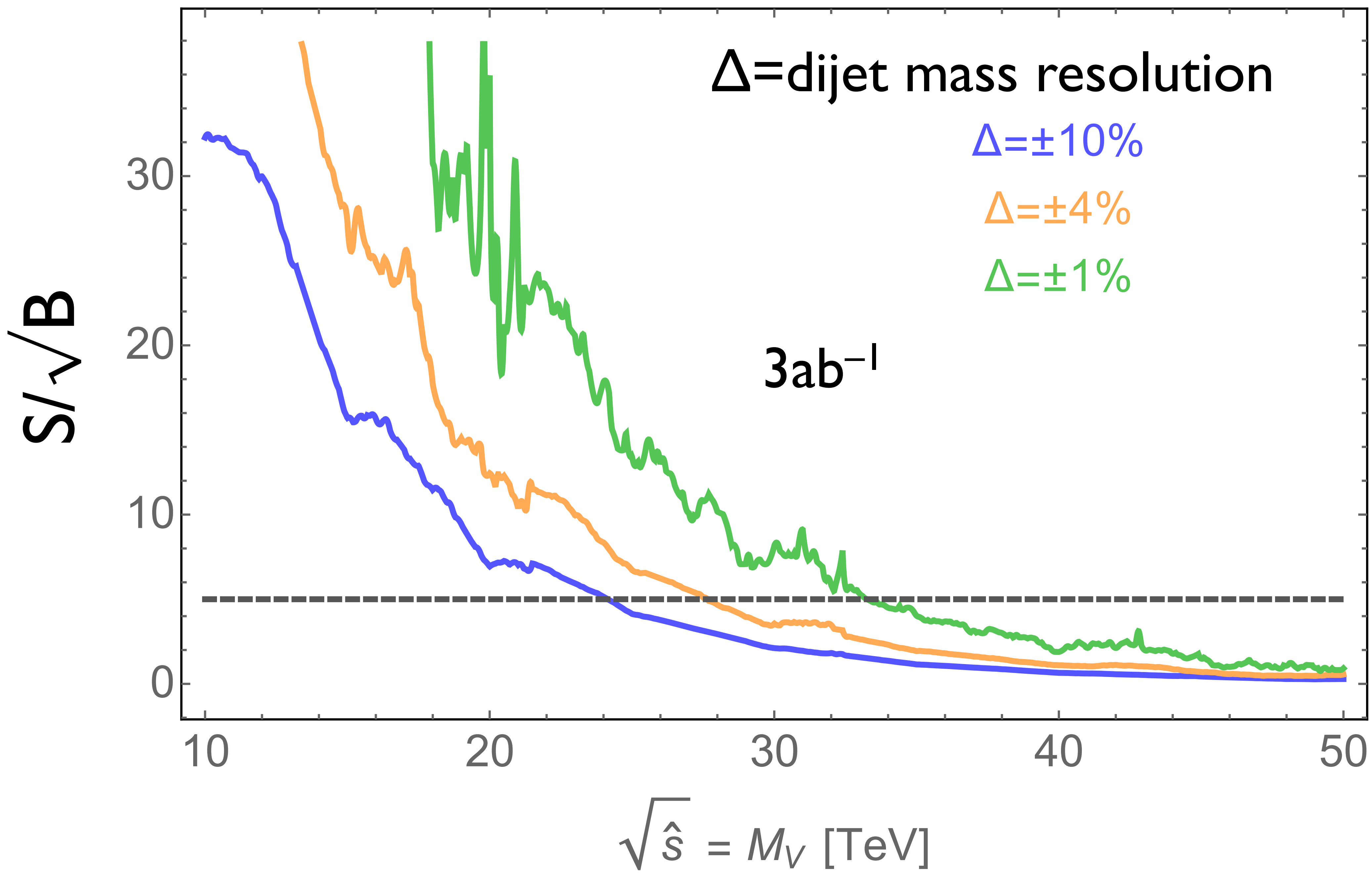
Sensitivity

Luminosity (fb^{-1}) to discover at 5sigma

	5TeV	8TeV	10TeV	20TeV	30TeV	40TeV
Nominal	0.15	0.93	2.39	91.2	1770	29983
10%	0.15	0.96	2.51	106.1	2312	48914
20%	0.16	1.02	2.72	123.9	2932	62653
30%	0.16	1.09	2.93	140.9	3674	91116
40%	0.17	1.18	3.14	159.4	4462	134534



Compare with discovery reach in dijet channel



Remarks

- At these masses, dijets may provide comparable discovery reach for Z', provided energy resolution in the 4-5% range ⇒ can far can we push jet performance at the highest E_T ?
- Observation reach in dimuon not terribly compromised by resolution going from 10 to 30-40% at 10 TeV ⇒ BL^2 increase by 2-3 may be sufficient
  - in ~absence of DY bg, studies of angular distributions, couplings, etc are not affected by worse δp_T
- More compelling physics cases may be invoked to request $7\times BL^2$:
  - spreading out dense jets, b-tagging, etc.
- Are there different, stringent performance requirements for muons, leading to different constraints on teh detector design?
  - E.g. mass resolution and trigger efficiency for $H\to\mu\mu$?

Jets at high E_T

see also
Brock Tweedie talk at this wshop

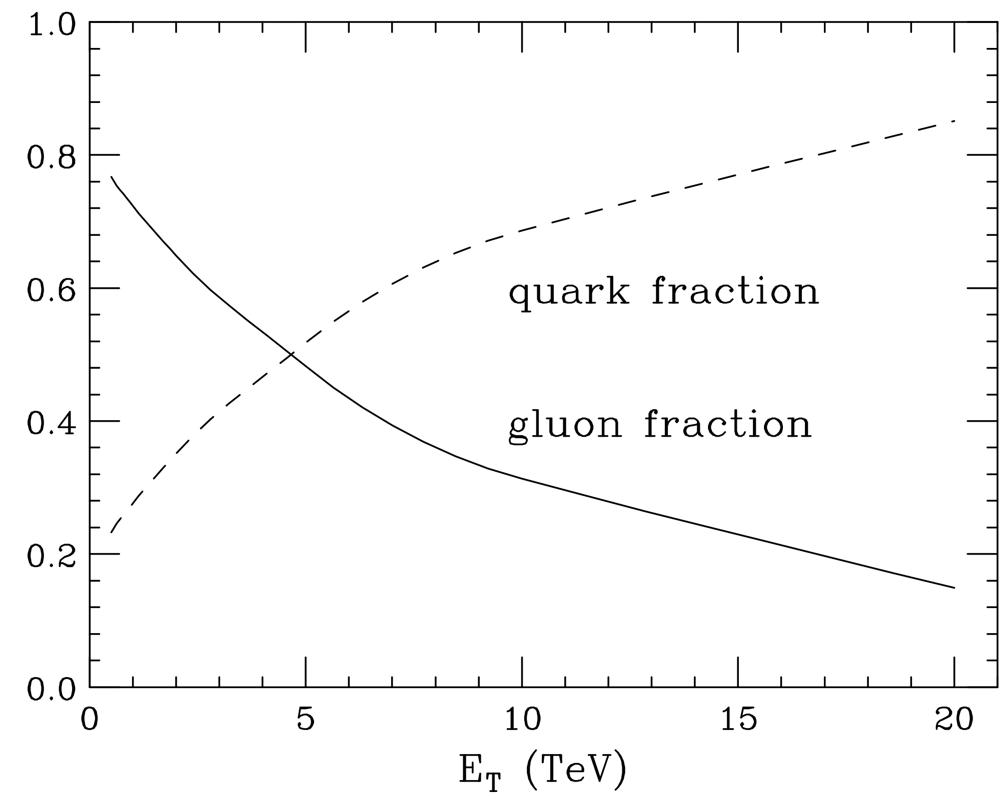
Consider some features of jet structure at high E_T. Compare jets from:

- top quark (hadronic) decay
- bottom quark
- inclusive jets
- W hadronic decay

Jets are defined by anti-k_T . Use R=1 to define jet, then look inside at smaller R. No soft UE, no pileup.

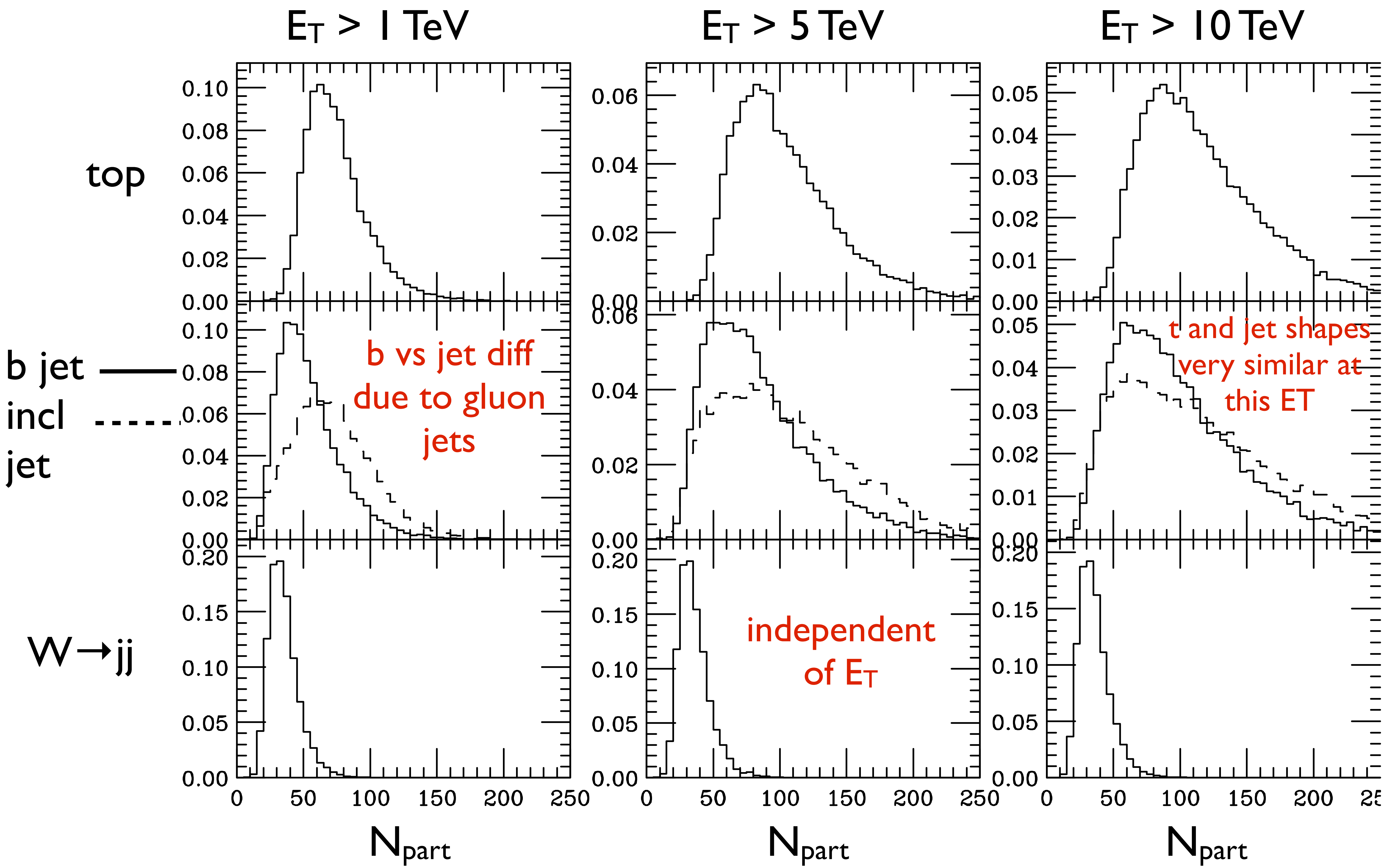
Generation: Alpgen + Herwig

NB: Inclusive jets here means jets from the QCD background. Thus they include a mixture of light quark and gluon jets, which varies vs E_T

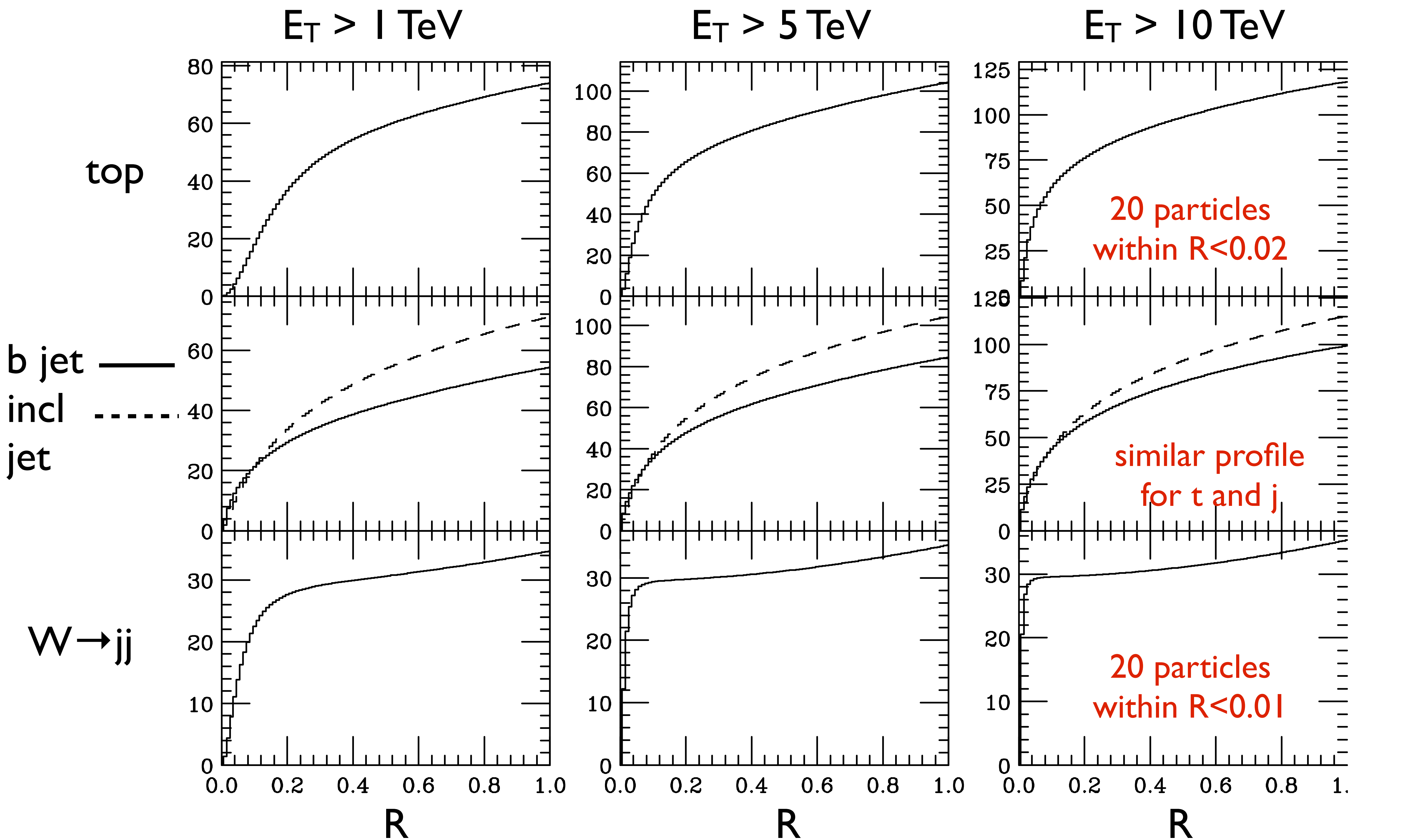


Particle multiplicity distribution: $1/\sigma\ d\sigma/dN_{part}$

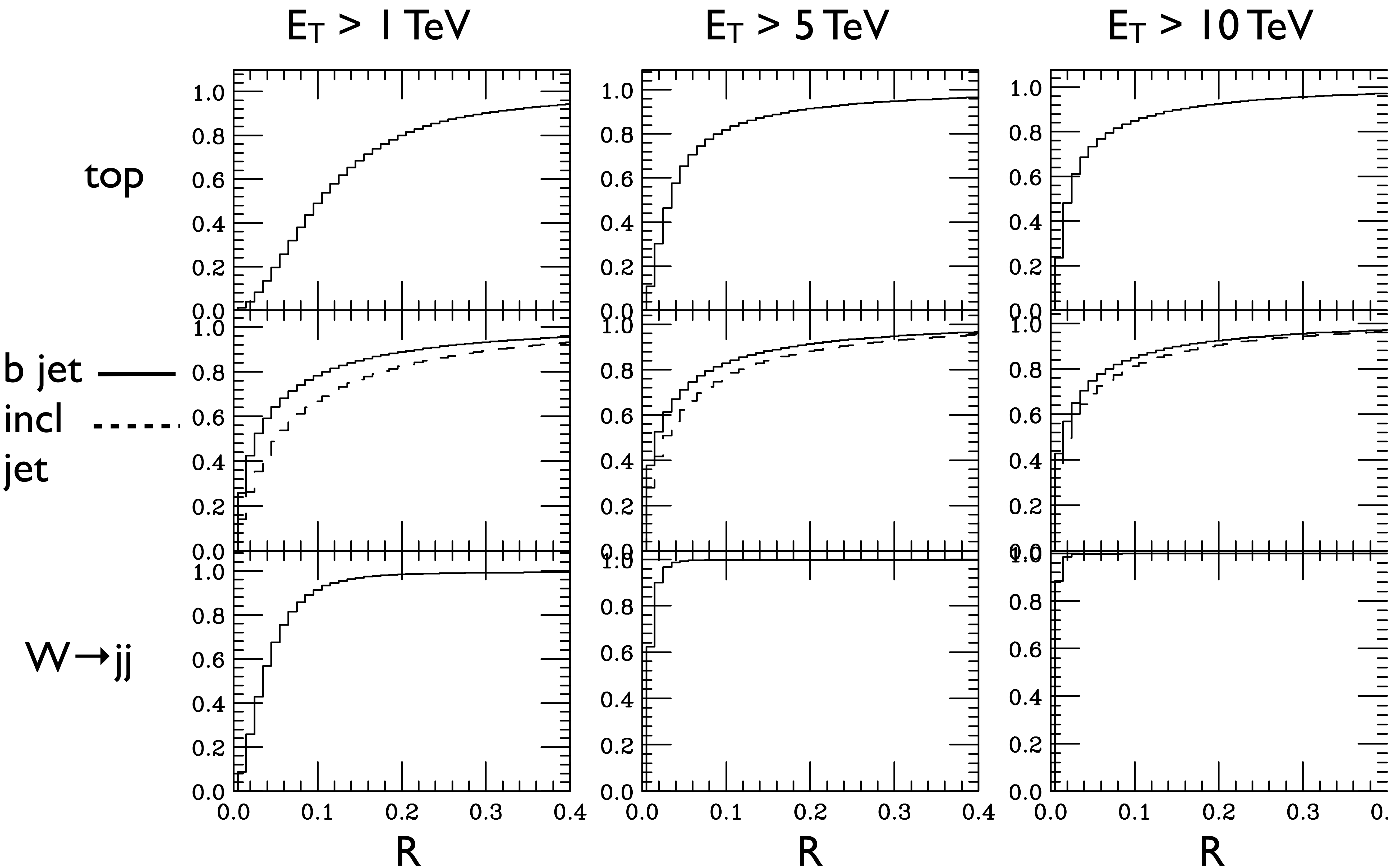
(particle: everything except neutrinos, neutral and charged, with stable π^0)



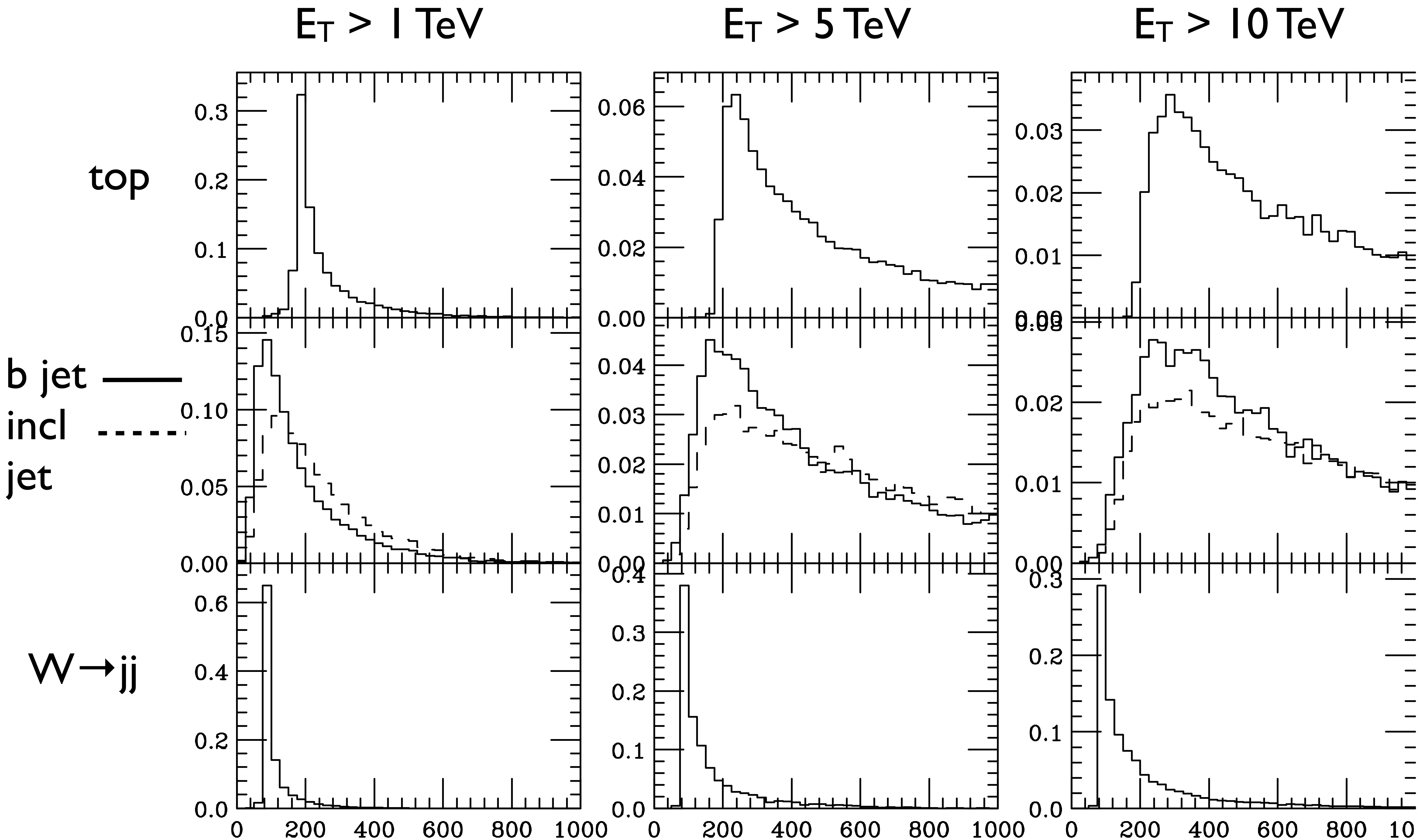
Average particle multiplicity shape: N_{part} (r<R)



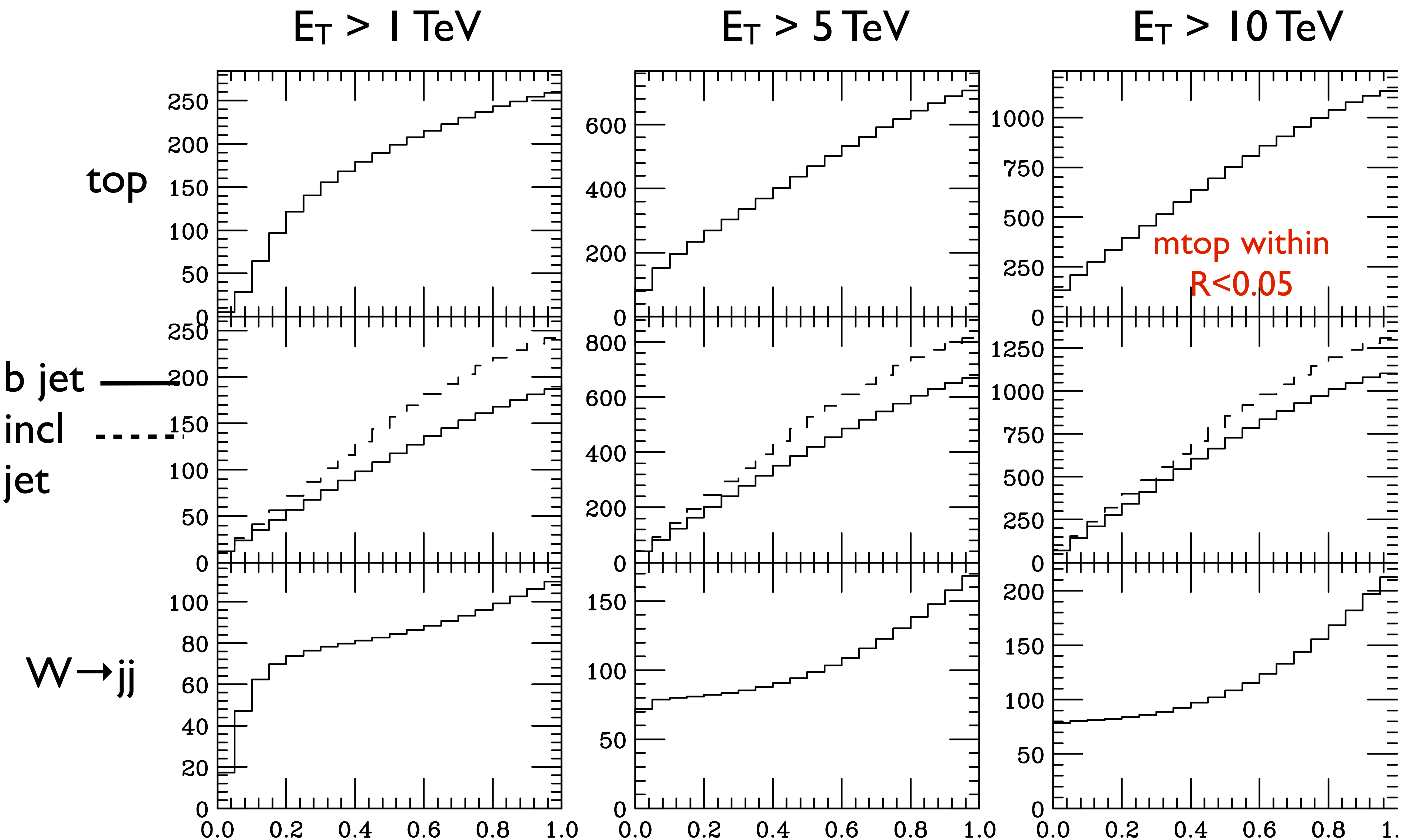
Energy shape: E(r<R) / E(r<1)



Jet mass distribution: $1/\sigma \, d\sigma/dM_{jet}$



Average jet mass: M(particles with r<R)



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- For CERN, the scale of the project may require not just international participation, beyond the CERN member states, but also engagement of other science communities (low-energy nuclear physics, light sources, medical sciences, applied accelerator physics, advanced technology, ...)
- While the above has not entered our radars as yet, the least we can envisage today is maintaining at the FCC a rich and diverse HEP programme, fully exploiting the injector chain (fixed target experiments) and the beam options (heavy ions). The FCC study is mandated to explore these opportunities as well, and assess their impact on the whole project.